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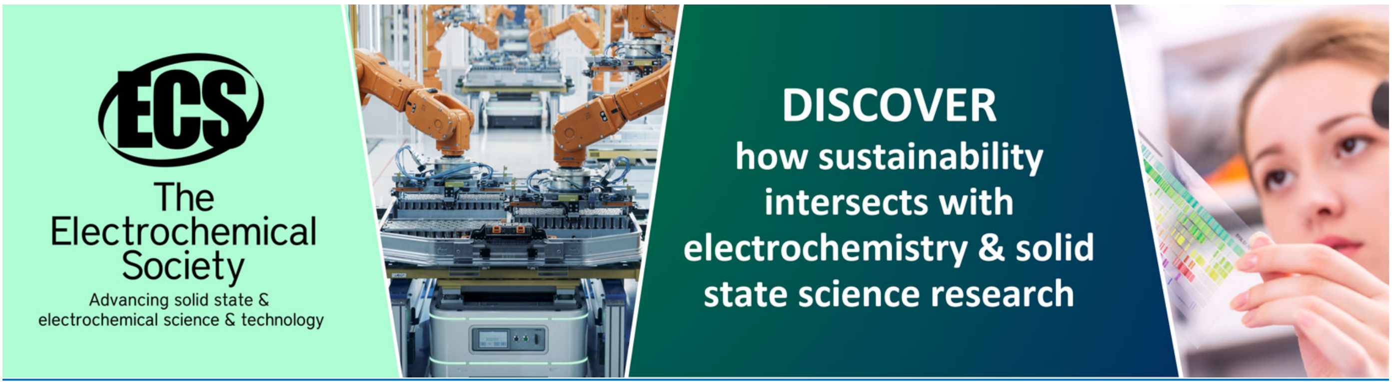

Exploring driving factors of soil erosion using a Multiscale GWR model: a case study at Central Citarum Watershed, West Java, Indonesia

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Abstract. To address challenges in soil erosion management and ecological rehabilitation, understanding the determinants of soil erosion is crucial. This research aims to achieve two primary objectives: (1) delineating the spatial patterns of soil erosion within the designated region and (2) identifying the influential factors using the Multiscale Geographical Weighted Regression (MGWR) methodology. The methodological framework involved the creation of grid datasets, with soil erosion as the response variable and a combination of physical and socioeconomic attributes as predictors. We extracted 550 data points from raster datasets, specifically centered on village locations, using the 'extract multi-value to point' tool in ArcGIS. The R Studio environment was utilized to select the relevant factors influencing soil erosion. The geographical detector technique was applied to determine the explanatory power of each determinant concerning the spatial patterns of soil erosion. Subsequently, data from the Ordinary Least Squares (OLS) model underwent MGWR analysis. The findings reveal that the Central Citarum Watershed experiences an estimated annual soil erosion of 23.16 million tons, averaging 102.01 tons per hectare. The analysis identified LS (slope length and gradient) and CP (vegetative cover and supportive practices) as the primary variables influencing the spatial variability of soil erosion. Notably, the MGWR model demonstrated enhanced explanatory capacity and effectiveness compared to both the OLS and Geographically Weighted Regression (GWR) methodologies.

1. Introduction

Soil erosion often leads to land degradation, agricultural production reduction, and environmental deterioration, which seriously restricts the sustainable development of regions [1]. Various factors influence the intensity of soil erosion, including topography, vegetation cover, rainfall, and soil texture. For instance, slope gradient directly impacts the rate of soil erosion, while the presence of vegetation cover can mitigate the erosive effects of heavy rainfall on the soil surface. In order to effectively address soil erosion and facilitate ecological restoration, it is essential to study the driving factors behind soil erosion and implement robust planning and monitoring strategies for soil erosion control [2].

Soil erosion is a widespread environmental problem that significantly impacts soil fertility, agricultural productivity, and water quality. In Indonesia, soil erosion is particularly severe in the Central Citarum Watershed, located in West Java, one of the country's most densely populated and intensively cultivated regions. The combination of steep slopes, heavy rainfall, and extensive land use practices, such as agriculture and deforestation, has accelerated soil erosion rates in this region [3]. These factors have contributed to the loss of valuable topsoil, reduced crop yields, and increased sedimentation in rivers and reservoirs, affecting local communities' agricultural productivity and water availability [4].

In addition to issues related to water availability and quality, the Citarum Watershed is grappling with challenges posed by soil erosion and sedimentation. Climate change and land use changes have emerged as the primary causes of these problems. Consequently, there is a pressing need to prioritize monitoring soil erosion within the expansive Central Citarum Watershed, spanning an area of 227,020 hectares. Extensive research has been conducted to comprehend the underlying factors driving soil erosion in this region. Previous studies have identified various contributors to soil erosion, such as topography, land use patterns, soil types, and rainfall patterns [5]. However, due to these factors intricate and multiscale nature and complex interactions, relationships between driving factors and soil erosion can exhibit spatial variations. This phenomenon underscores the need to employ a spatially explicit modeling approach to capture these dynamics effectively.

Multiscale Geographically Weighted Regression (MGWR) is a spatial regression technique that examines spatially varying relationships between variables at multiple scales. MGWR extends traditional Geographically Weighted Regression (GWR) by incorporating multiple bandwidths, each corresponding to a different scale of analysis. This approach recognizes that spatial relationships can vary in strength and form across different spatial scales and allows for a more nuanced understanding of these relationships. MGWR is particularly useful in contexts with complex and heterogeneous spatial relationships between variables. It can be applied to various research questions related to social, economic, and environmental processes [6].

This observation is consistent with earlier research underscoring the superiority of the GWR model over the Ordinary Least Squares (OLS) technique in examining the determinants of environmental processes. For example, a study by Oshan [7] posited that the GWR model offers a more robust methodology for discerning spatially differentiated relationships compared to the OLS technique. The GWR framework takes into account regional nuances and provides geographically tailored insights into the impact of associated variables on changes in water yields [8].

Terrain, plant cover, rainfall, and soil composition, among other elements, collectively influence the magnitude of soil erosion. For instance, the gradient of the land impacts the rate of soil erosion, while the vegetative cover mitigates the direct abrasion of the soil surface from intense precipitation. Investigating the determinants of soil erosion and quantifying their effects is pivotal in formulating effective strategies for soil erosion mitigation and ecological rejuvenation [2].

The Central Citarum Watershed emerges as a fitting locale for MGWR application, given its distinct spatial variations in topographical features, land application, and soil characteristics. As such, this research is directed towards examining the contributors to soil erosion within the Central Citarum Watershed in West Java, Indonesia. The investigative goals include: (1) charting the spatial patterns of soil erosion throughout the Central Citarum domain and (2) pinpointing the variables inducing soil erosion through the MGWR framework. The projected results from this inquiry are set to augment our grasp of the foundational triggers of soil erosion in the Central Citarum Watershed, thus furnishing critical perspectives for the design of adept management and counteraction measures.

2. Materials and Methods

2.1. Study area

The study was undertaken in 2022 within the Central Citarum sub-watershed, encompassing 17 minor sub-watersheds. From an administrative perspective, this region is divided into 52 sub-districts, spanning five regencies: Bandung, Purwakarta, Sumedang, Cianjur, and Bogor. Geographically it is located between 107º22'50,606" E – 107º56'46,297" E and 6º45'40,112" S – 7º14'27,018" S, as represented in Figure 1.

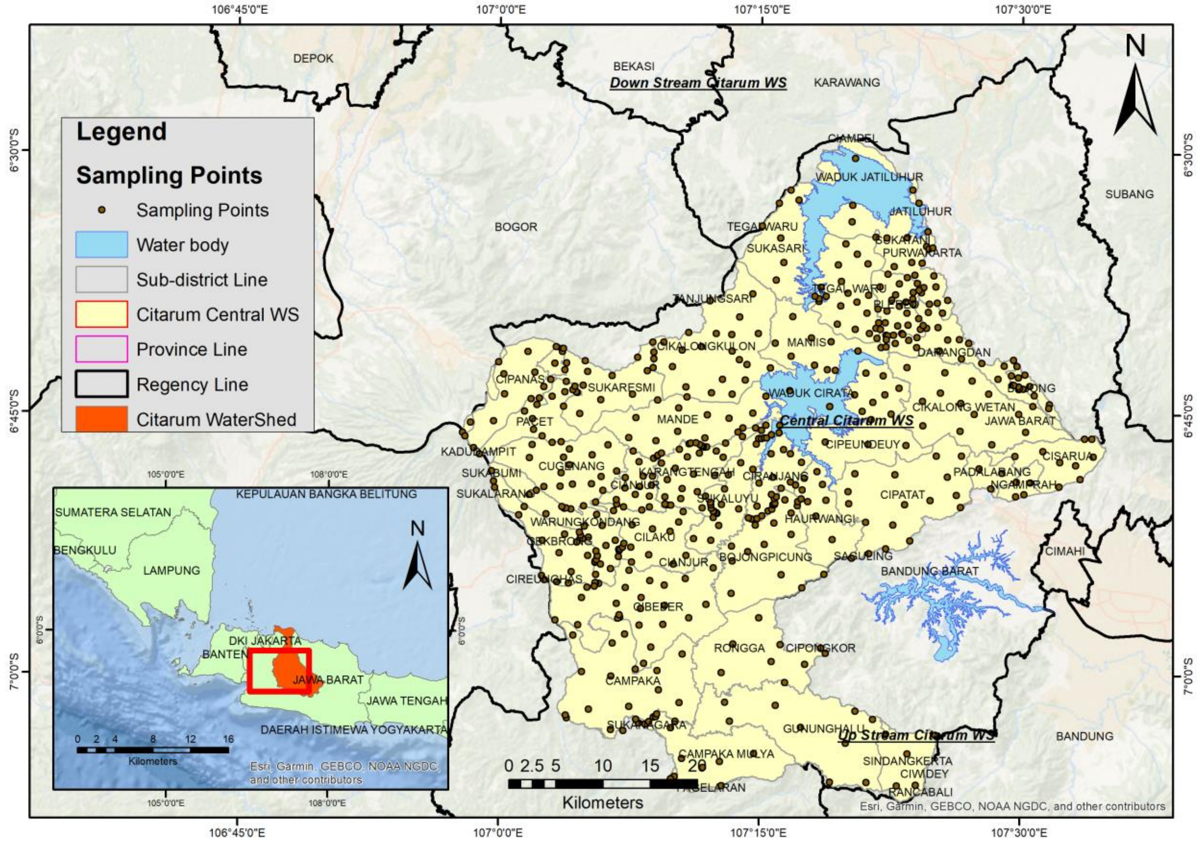


Figure 1. Location of the study.

2.2. Data

In this research, we utilize both spatial and tabular data. Soil erosion data are sourced from the research conducted by Suryanta [9], while Gross Regional Domestic Income (GRDI) and Population Density (POP) data are obtained from BPS West Java [10]. The necessary data for this study are presented in Table 1.

The socioeconomic data, in tabular format, is integrated with sub-district polygon data, and we subsequently analyze and convert it into raster data. The input data are transformed into a raster data format with a spatial resolution of 30 m x 30 m, referenced to the WGS84 datum.

The processes and procedures for calculating soil erosion were carried out using the SDR model tool with the help of the InVEST 3.9.0 platform from the Natural Capital Project. [9,11]. It's important to note that we did not conduct this analysis but utilized the soil erosion maps generated by Suryanta's research in 2022 [9].

To assess the magnitude of soil erosion in the Central Citarum region, soil erosion maps (in data grid format) are summarized using sub-district boundary polygons through the zonal statistical tool available in the ArcGIS platform [12]. According to the official document of the Indonesian government, soil erosion can be classified into five distinct levels: very slight (<15 ton $ha^{-1}y^{-1}$), slight (15 - 60 ton $ha^{-1}y^{-1}$), moderate (60 - 180 ton $ha^{-1}y^{-1}$), severe (180 - 480 ton $ha^{-1}y^{-1}$), very severe (> 480 ton $ha^{-1}y^{-1}$) [13]. The research is divided into three sections, as shown in Figure 2.

Table 1. List of required data inputs for the InVEST model.

Data	Data Type	InVEST Model	MGWR Model
Physical data			
Digital Elevation Model (DEM)	Raster file (.tif)		
a slope length-gradient factor (LS)		☑	☑
Isoerosivity map (R factor)	Raster file (.tif)	☑	☑
Soil Erodibility map (K factor)	Raster file (.tif)	☑	☑
Boundary shapefile (Watershed)	Vector file (.shp)	☑	
Land cover map	Raster file (.tif)	☑	☑
Biophysical data	matrix (.csv)		
a support practice factor P USLE		☑	☑
a crop-management factor C USLE		☑	☑
Socioeconomic data			
Gross Regional Domestic Income (GRDI)	Tabular (.xls)		☑
Population Density (POP)	Tabular (.xls)		☑

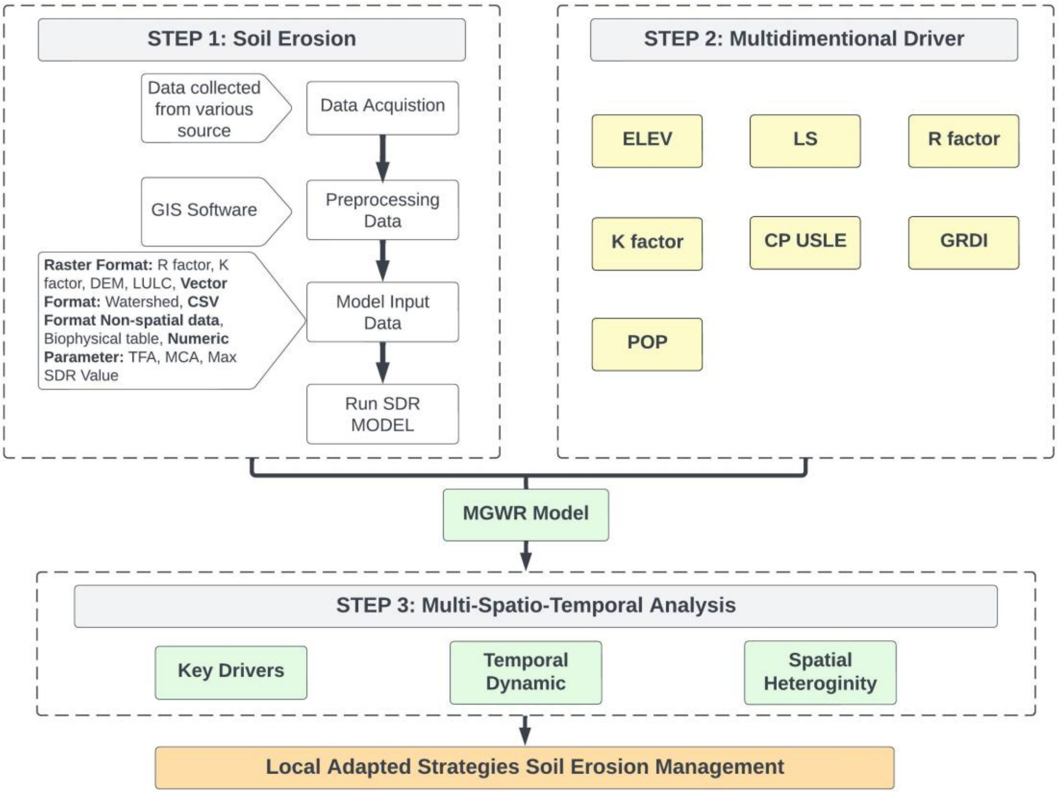


Figure 2. The research framework.

The first stage focuses on soil erosion (the dependent variable), while biological and socioeconomic data are generated as independent variables in grid format. Soil erosion and the variables influencing it, in raster format, are then extracted based on 550 data points located at the central points of villages using the 'extract multi-value to point' tool in ArcGIS. In the second stage, we select the driving factors for soil erosion, which are limited to: the K factor (X1), R factor (X2), ELEV (X3), LS (X4), C and P USLE (X5), GRDI (X6), and POP (X7).

The analysis was conducted using the R Studio platform. To obtain an optimal regression model, the initial step involved selecting key variables, removing unnecessary ones, and ensuring that explanatory variables were not multicollinear, as determined by the Variance Inflation Factor (VIF) values. We removed driving factors with a VIF greater than ten, indicating multicollinearity among those variables [12,14].

In the third stage, we perform MGWR modeling. The dependent and independent variables, generated through the OLS model approach, are subsequently analyzed using the MGWR approach to determine whether the model is global or local. To investigate the spatial relationship between the dependent variable (soil erosion) and explanatory variables (physical and socioeconomic factors), we employ the MGWR model with fixed bandwidth selection. The MGWR model is expressed as follows: [15]:

$$y_i = \sum_{j=1}^{n} a_j x_{ij} + \sum_{j=n+1}^{m} \beta_j \ (\mu_i \gamma_i) \ x_{ij} + \varepsilon_i \tag{1}$$

where (μi, γi) is the geographical coordinates of the sub-district, *j* is the number of cities, $a_j aj$ is the regression coefficient of the global variable, x_{ij} is the observed value of the *jth* variable at position *i*, β_j is the regression coefficient of the local variable, and εi is the random error term.

Afterward, a variable ranking process was conducted to identify the essential variable in the model based on its contribution rate. The contribution rate was determined by comparing the difference in the Residual Sum of Squares (*RSS*) value between the Multiple Linear Regression (*MLR*) results with all variables (*RSS_i*) and the results without the variable under consideration (*RSS_j*). As the Contribution Rate (*CR*) values are relative, they were aggregated to sum up to 100, representing the overall predictors. The calculation formula for the *CR* is as follows [12,16]:

$$CR\ (\%)_{(j)} = \frac{RSS_j - RSS_i}{RSS_j} * 100 \tag{2}$$

To generate spatial distributions from sampling points, we employed a widely adopted geostatistical interpolation technique, such as Kriging [17] with a spherical parameter for the semi-variogram and a search radius setting of twelve minimum points. Kriging utilizes the spatial autocorrelation of the sampled data to estimate values at unobserved locations, facilitating the creation of continuous maps that depict underlying spatial patterns, capture spatial variability, and provide accurate representations of MGWR factors across the study area.

3. Result and Discussion

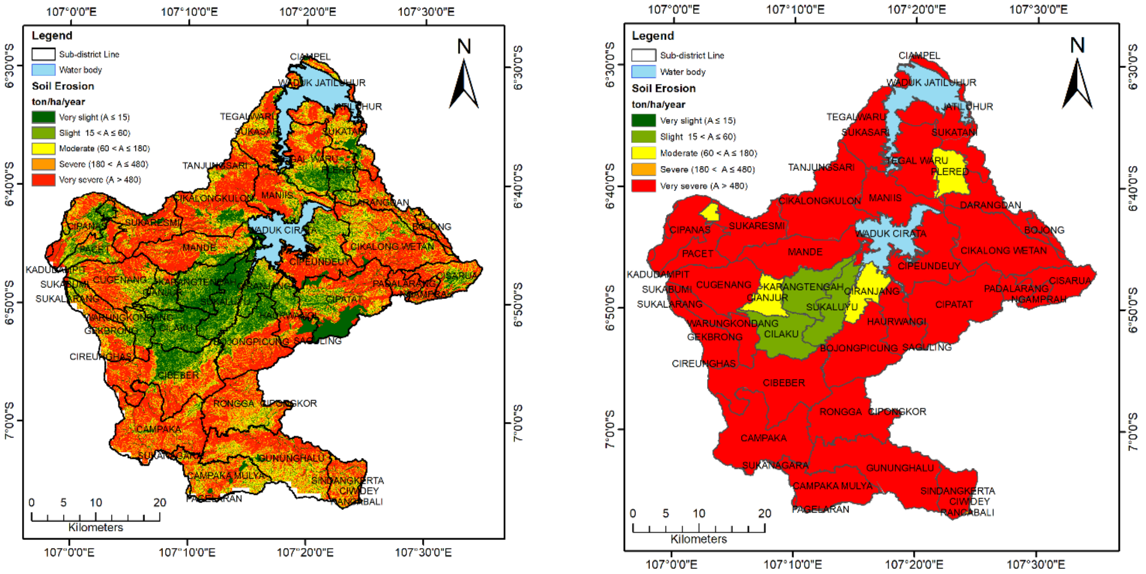
3.1 Soil erosion

Based on the calculations conducted using the InVEST model, we present the spatial distribution characteristics of soil erosion at both grid and sub-district scales in Figure 3. The zonal statistical analysis results provided the average erosion rate for each district, which is presented in Table 2.

According to the standard document from the Indonesian government (The Ministry of Environment and Forestry) [13], the Central Citarum area experiences soil erosion ranging from 32.66 to 3,931.73 tons/ha/year, with a total soil erosion loss of 23.16 million tons per year. This is equivalent to an annual average of 102.01 tons per hectare.

Table 2. Soil erosion in Central Citarum Watershed (based classified by [13]).

Scale	Very slight	Slight	Moderate	Severe	Very severe
Pixel (ha)	47,673.36	27,241.92	31,782.24	36,322.56	83,995.92
Pixel (%)	21	12	14	16	37
Sub-district (n)	3	3	7	1	38
Sub-district (%)	5.77	5.77	17	2	73



(a) Soil Erosion at the grid scale (b) Soil Erosion at the sub-district scale

Figure 3. Spatial distribution of soil erosion in Central Citarum Watershed: (a) at the grid scale, (b) at the sub-district scale.

Based on the scale grid analysis, the dominant category of soil erosion severity is classified as "very severe," covering an area of 83,995 hectares (37% of the total area). This dominance is primarily observed in Campaka, Sukaresmi, Padalarang, and Kadulampit sub-districts. The next category is "very slight," encompassing 47,673 hectares (21% of the total area), with prominent occurrences in Cilaku, Sukaluyu, Karangtengah, and Ciranjang sub-districts. The "severe" category occupies 36,322 hectares (16% of the total area) in Sukaresmi and Cipanas sub-districts. The "moderate" category spans 31,782 hectares (14% of the total area) in Gununghalu, Rongga, and Sindangkerta sub-districts. Lastly, the "slight" category with severe erosion covers 27,241 hectares (12% of the total area) in the Plered sub-district.

At the sub-district scale, the dominant category of soil erosion severity is classified as "very severe," encompassing 38 sub-districts (73% of the total). This dominance is observed in various sub-districts, including Campaka, Cikalong Kulon, Cisarua, Bojongpicung, Kadulampit, and Tegalwaru. The next category is "moderate," comprising seven sub-districts (17% of the total), including Plered, Cianjur, and Ciranjang. Lastly, the categories of "slight" and "very slight" are represented in 3 sub-districts (5.77% of the total) each, namely Cilaku, Sukaluyu, and Karangtengah, respectively.

A study conducted by Chaidar in the upper reaches of the Citarum Watershed between 1990 and 2013 revealed varying soil erosion rates, ranging from 62.04 to 137.66 tons per hectare annually, with an average of 107.99 tons per hectare per year. This data highlights a consistent increase in soil erosion within the Citarum region during the specified period [18]. Karlina's investigation into the erosion dynamics of the upper Citarum Watershed in Bandung Regency found that the predominant erosion categories were Level 2 (16-60 tons per hectare) associated with arid land agriculture and Level 3 (60-180 tons per hectare) characterized by a combination of orchards and secondary woodlands [19]. Other studies have emphasized the role of vegetation types in influencing erosion rates [20]. Specifically, in the upper Citarum region in 2020, within the Mandalahaji village of the Bandung sub-district in West Java, monocultural landscapes experienced erosion at a rate of 14.95 tons per hectare annually, while regions dominated by agroforestry practices had erosion rates of 1.5 tons per hectare each year [21].

Ambarwulan's research [22] indicates that erosion classes in the Middle Citarum Watershed are higher than previous findings. In the Middle Citarum Watershed, erosion rates range from 0.87 to 495.30 tons per hectare per year due to a more extensive study area, diverse land cover, and varying slope classes [22].

3.2 Multiscale GWR model

Through stepwise regression analysis, we conducted a multicollinearity test among the explanatory variables (Table 3). The results of the OLS fit indicated that the VIF for all variables was below 10, indicating the absence of variable redundancy and multicollinearity among the factors. However, the Jarque-Bera test revealed that the residuals deviated from a normal distribution, suggesting a biased model fit. Therefore, it is advisable to incorporate the GWR model to enhance fitting precision. Table 4 presents the global, GWR, and MGWR models derived from the OLS analysis.

Table 3. Multicollinearity test between explanatory variables.

Variable	K factor	R factor	ELEV	LS	CP	POP	GRDI
VIF	1.254	3.3416	3.8285	2.4984	1.2699	8.9012	1.811

Table 4. Comparative analysis of the MGWR and OLS/GWR models.

	R^2	Adjusted R^2	AIC	AICc
OLS	0.287	0.277	1,391.063	1,393.397
GWR	0.833	0.777	853.222	948.017
MGWR	0.954	0.928	262.520	483.965

The comparative analysis presented in Table 4 highlights the superior performance of the MGWR model when compared to its OLS and GWR counterparts in elucidating the spatial patterns and determinants of soil erosion within the Central Citarum Watershed. With an impressive R^2 value of 0.954, the MGWR model demonstrates exceptional explanatory power, accounting for approximately 95.4% of the variance in soil erosion. In contrast, the OLS model has an R^2 of 0.287, and the GWR model has an R^2 of 0.833. Additionally, the MGWR model exhibits an elevated adjusted R^2 value of 0.928, indicating a better fit to the spatial intricacies and disparities of the influencing variables. The reduced AIC and AICc metrics associated with the MGWR model suggest an optimal balance between model fidelity and complexity, surpassing both the OLS and GWR models. These findings underscore the efficacy of the MGWR model in discerning spatial fluctuations and regional impacts of causative factors, providing critical insights for soil erosion mitigation and ecological restoration measures within the Central Citarum Watershed.

It's important to note that the overarching regression model is ill-suited for forecasting soil erosion as it fails to capture the intricate relationship between soil erosion and its determinants. On the other hand, while the GWR model adeptly addresses spatial disparities, it primarily captures the optimal mean scale of non-stationary spatial interactions between the dependent variable and all independent variables.

This observation aligns with Nahib's study [12], which suggests that the GWR model elucidates the locale-specific and nuanced roles of relevant factors in modulating water yield fluctuations. In contrast, OLS merely provides global coefficients for each explanatory determinant. The MGWR model, an evolution of the GWR, captures non-stationary spatial interactions by considering the optimal bandwidth of multiple independent variables, effectively addressing the challenges mentioned [23,24].

As demonstrated in the visualizations in Figure 4, the localized spatial regression model based on MGWR provides a more comprehensive portrayal of the impacts of the aforementioned determinants on soil erosion.

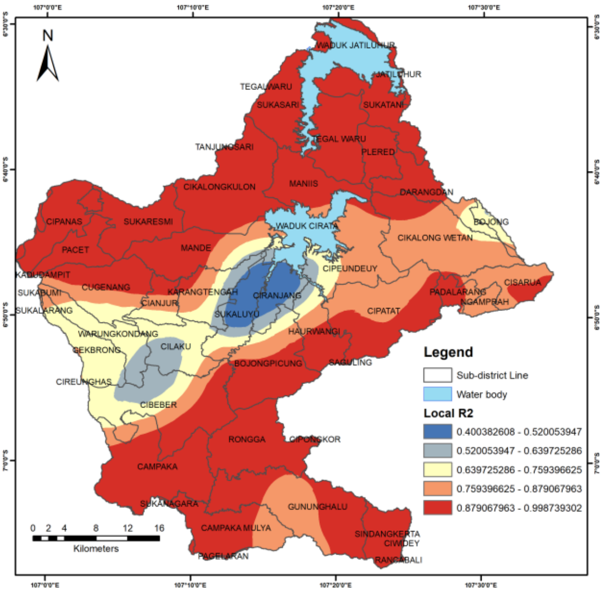
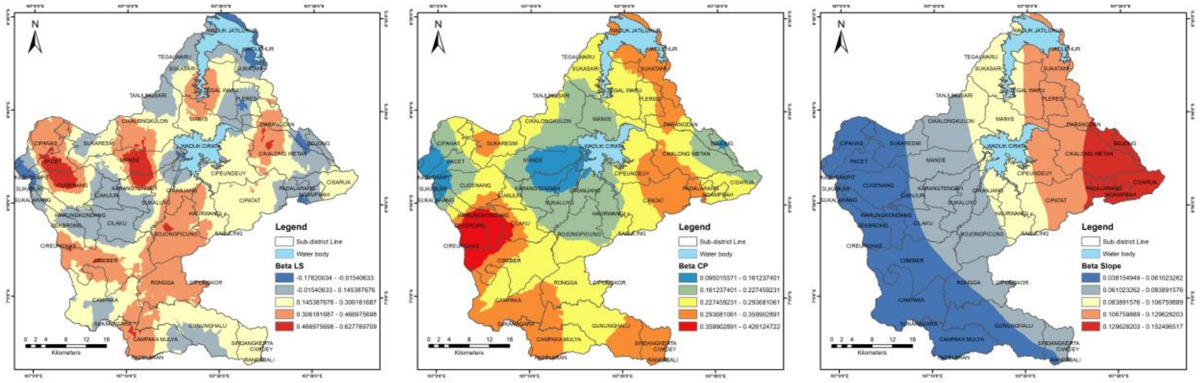


Figure 4. Local R^2 spatial distribution of the relevant results of the MGWR model.

This local R^2 mapping can be employed to assess whether an area necessitates additional explanatory factors for a better understanding of the underlying mechanisms influencing soil erosion. As depicted in Figure 4, the northern region, comprising Sindangkerta, Ciwidey, Rancabali, Rongga, Campaka, Sukanagara sub-districts, and the southern region, including Cipanas, Sukaresmi, Cikalongkulon, Plered, Tanjungsari, Tegalwaru, Cipanas, Sukasari, and Sukatani sub-districts, exhibit higher local R^2 values compared to the central part, consisting of Ciranjang, Sukaluyu, Cilaku, Cireunghas, Cekbrong, and Warungkondang sub-districts. These areas predominantly fall into the medium (yellow) to high (red) value categories. On average, the local R^2 values indicate a moderate (0.6) to high (0.9) relationship. The variation in R^2 values among different areas highlights the influence of location-specific heterogeneity, which shapes soil erosion values. Based on the MGWR output, a visual analysis of the correlation coefficient for each driving factor was conducted using the ArcGIS spatial distribution module, as illustrated in Figure 5 and detailed in Table 5.



5a. Distribution of beta LS **5b**. Distribution of beta CP **5c**. Distribution of beta Slope

Figure 5. MGWR coefficients between soil erosion and driving factors.

Table 5. Mean statistics of MGWR coefficients between soil erosion and driving factors.

Variable	K factor	R factor	Slope	LS	CP	POP	GRDI
Mean	-0.005	-0.035	0.082	0.494	0.255	-0.018	-0.022

As shown in Figure 5 and summarized in the table, the LS coefficient values range from -0.176 to 0.627, with a mean value of 0.494. The distribution of LS coefficients across regions demonstrates a unique pattern. Specifically, the north region, including Jatiluhur, Sukatani, Plered, and Tegalwaru sub-districts, and the east side encompassing Bojong, Padalarang, Ngampah, Cipatat, and Cipeundeuy, exhibit smaller values predominantly in the low to medium range. In contrast, the west and central regions comprising Mande, Cugenang, and Pacet sub-districts feature higher LS coefficient values.

The CP value of the variable regression coefficient ranges from 0.095 to 0.426, with an average of 0.255. The distribution of coefficients is characterized by a variation in magnitude across different regions. The west-central region, encompassing Cipanas, Pacet, Kadudampit, Sukabumi, Sukalarang, Mande, Karangtengah, Sukaluyu, Bojongpicung, and Haurwangi sub-districts, predominantly exhibits low to moderate coefficients. Conversely, the west-south region, comprising Warungkondang, Gekbrong, Cireunghas, Campaka, Sukanagara, Campaka Mulya, Sindangkerta, Ciwidey, and Rancabali sub-districts, demonstrates medium to high coefficient values.

Furthermore, the regression coefficient of the Slope variable ranges from 0.038 to 0.152, with an average of 0.082. The distribution of coefficients reveals a similar pattern across regions. The west-central region, which covers most districts in Cianjur Regency, and the southern part, including Bojong Picung, Haurwangi, Saguling, Gununghalu, Sindangkerta, and Ciwidey (West Bandung Regency), predominantly exhibit low to medium coefficient values. In contrast, the central region (Cipeundeuy, Cipatat sub-districts), the northern region (Purwakarta Regency), and the western region (West Bandung Regency) tend to have medium to high coefficient values.

These coefficient values provide valuable insights into the variability and distribution of the LS, CP, and Slope variables across different regions. Such findings contribute to a better understanding of the relationships and potential impacts of these variables within the context of the studied factors, offering valuable guidance for soil management and erosion control strategies.

This finding is in line with the results of Ge’s research in China, showing that the main driver of soil erosion was the cover management factor, while the second was the length of the slope and the slope factor. Meanwhile, at different erosion intensity values, the driving force of each factor shows non-linear inhibition and complex effects with changes in factor values [1].

In Nahib's study [12], it was observed that interactions exist between several factors, namely the K factor and Slope, R factor and Slope, LS and Slope, and K factor and CP, resulting in bivariate enhancements. These findings indicate that soil erosion's impact is influenced by the combined effect of multiple driving factors, surpassing the influence of any single factor alone. Additionally, the study revealed variations in the nature of interactions among these factors. Furthermore, the remaining factors exhibited non-linear enhancement patterns. These findings contribute to a better understanding of the complexity and interplay of factors affecting soil erosion, providing valuable insights for soil management and erosion control strategies.

The results of multiple regression analysis using MGWR software identified nine variables with significant contributions to soil erosion (Table 6). Based on the regression coefficients, LS, CP, and Slope are the most dominant variables affecting soil erosion. The positive regression coefficients indicate that higher values of these variables contribute significantly to increased soil erosion. Furthermore, when considering the independent variable contributor rate to the amount of soil erosion, both models indicate that LS is the most dominant variable, with a contribution of 45.99% (OLS model) and 20% (MGWR). There are variations in the contribution rate for each variable.

Table 6. Estimates and p-values of different drivers for OLS and CR of soil erosion.

Variable	β	P value	CR (%)	
			OLS	MGWR
R^2			0.287	0.954
Driving factor				
K factor	0.011	0.766	6.73	13.50
R factor	0.024	0.555	7.15	13.44
Slope	0.083	0.038	7.55	17.91
LS	0.417	0.000	45.99	20.10
CP	0.232	0.000	7.05	13.57
POP	-0.081	0.049	18.14	7.98
GRDI	0.028	0.513	7.40	13.49

In the Middle Citarum Watershed, erosion ranges from 0.87 to 495.30 tons per hectare per year due to the larger study area, diverse land cover, and varying slope classes [22]. Furthermore, the MGWR model analysis results are used to determine the relationship between independent variables and soil erosion. Based on the CR formula, the contribution rate obtained is LS > Slope > CP > K factor > GRDI > R factor > POP. LS is revealed as the primary controlling factor for soil erosion, with the three dominant variables contributing a total of 61.58%. The highest contributions come from the LS factor (20.10%), Slope (17.91%), and bare CP (13.57%).

Socioeconomic determinants, namely POP and GRDI, exhibit both positive and negative correlations with soil erosion. An increase in per capita GRDI tends to boost infrastructure and the extent of built-up regions. However, the expansion of such built-up spaces can escalate surface water volumes, leading to intensified soil erosion. The GRDI per capita variable contributes 13.49%. Conversely, an increase in population density, particularly among those with a heightened awareness of natural resources and environmental sustainability, can mitigate soil erosion within a region. The influence of the POP variable is relatively minimal, at 7.98%.

A parallel investigation conducted in the Jihe Basin of China [25] reveals that MGWR outcomes pinpointed slope as the paramount determinant influencing soil erosion at watershed scales. The mean coefficients for slope, forest cover, and grass cover were observed to be 0.90, -0.11, and -0.19, respectively, indicating that the impacts of these factors manifest across varying scales.

Land use factors and conservation practices have become the primary influencers of soil erosion. Developing a comprehensive land strategy is crucial, especially in regions with high or very high soil loss rates. Vegetative approaches (such as implementing agroforestry, utilizing cover crops, and employing grass strips) can effectively address soil erosion. Additionally, mechanical measures like the construction of bund terraces and bench terraces can also contribute to erosion control. Implementing these strategies effectively mitigates soil erosion and promotes sustainable land management practices [26].

4. Conclusion

The findings reveal that the Central Citarum Watershed experiences an annual cumulative soil erosion of 23.16 million tons, averaging 102.01 tons per hectare. The outcomes of the spatial regression model underscore a robust association between the driving determinants and soil erosion, with noticeable disparities in the spatial dynamics and magnitude of this correlation. The primary factors influencing soil erosion include LS, CP, and Slope. Among the models examined, the MGWR model demonstrates superior explanatory power, surpassing both the OLS and GWR models in terms of effectiveness.

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